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Article

System Dynamics Modeling of Mongolia's Forest Fund and Forest Resources

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Abstract. The main objective of this research is to develop a dynamic model of the system to determine the future status of Mongolia's forest resources and forest fund areas, and to determine what risks and benefits are expected to arise in the future of Mongolia's forests, and when. This article is unique in that it calculates the biomass of growing Larch, cedar, and pine trees, which occupy the largest share of Mongolia's forest resources, using the mathematical method of system dynamic modeling in the Vensim program. According to our system dynamics model, the share of forest land in Mongolia's total area will remain relatively stable, but the share of forested land in total area is expected to decline from 8.07% in 2020 to 7.6% by 2080. The share of degraded and depleted forest land is also expected to increase to 2–3 times the current level. The main reasons for this are many factors, including improper use of natural forests, the impact of natural factors caused by climate change, and the lack of coordination of forest sector management policies. Also, the increase in the area degraded and depleted forest land is another reason for the decrease in the number of living trees per hectare of forest area and the increase in the area with dead, damaged, dried, and decayed trees. Larch, cedar, and pine trees are the most widespread trees in the forests of Mongolia, accounting for 94.15% of the total forest resources. The high average lifespan of these trees, which predominate in the natural forests of our country, is expected to lead to a shortage of forest resources in the future, which will negatively affect the growth of the environment, plants, and animals, as well as lead to many negative risks, such as a decrease in greenhouse gas absorption and a loss of forest ecological balance.

Keywords: Mongolian forest fund area, Mongolian forest resources, tree biomass, tree biomass system dynamics model, larch biomass, cedar biomass, pine biomass.

1 Introduction

Forest ecosystems play a critical role at the global scale by maintaining ecological stability, supporting local livelihoods, sequestering carbon, conserving biodiversity, and regulating hydrological regimes. However, the structure and functioning of forest eco--systems have been undergoing substantial changes in many regions worldwide due to anthropogenic pressures such as timber harvesting, forest fires, and land-use change as well as natural drivers associated with climate change. As a result, the sustainable use and management of forest resources has emerged as a major challenge for policymakers and natural resource managers, particularly in regions that are both economically dependent on forests and ecologically vulnerable.

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1.1 Mongolian forest fund area

84.9% of Mongolia's total forest area is covered by coniferous and deciduous forests in the northern part of the country, and 15.1% by saxaul forests in the southern Gobi and desert regions. Although the forest area is small compared to the total land area, the area per capita is 3.7 hectares, which is much higher than the world average of 0.54 hectares per person. As of 2020, the forest fund of Mongolia covered a total area of 18,608.0 thousand ha, accounting for 11.9% of the national territory. Of this area, 12,452.0 thousand ha were classified as forested land, including natural forests, planted forests, and shrublands. A further 5,634.4 thousand ha were identified as non-forested land, comprising sparsely wooded areas, lands undergoing natural regeneration or artificial afforestation, as well as forest lands degraded by wildfires, illegal logging, and pest infestations. In addition, 521.6 thousand ha were categorized as non-forest land within the forest fund [1]. It has been determined that the forest area of Mongolia has the following four soil types: 3,705 thousand ha of dark soil, 3,283 thousand ha of taiga permafrost soil, 7,394 thousand ha of taiga sod soil, and 2,063 thousand ha of ash soil, or a total of 16,445 thousand ha of forest area [2]. Therefore, 20% of the forest area is occupied by taiga permafrost soil, 12.5% by ash soil, 22.5% by dark soil, and 45% by taiga sod soil.

1.2 Mongolian forest resources

Forest resources constitute one of the most critical natural assets for countries worldwide in enhancing greenhouse gas sequestration and reducing emissions. Consequently, a key indicator of a country's contribution to achieving climate mitigation and sustainable development objectives is the accurate assessment of the status and composition of its national forest resources. As of 2020, the total growing stock volume of Mongolia's forests was estimated at 1,248,642,118 m^3, of which larch accounted for 79.28%, cedar for 8.91%, birch for 5.96%, pine for 4.95%, spruce for 0.23%, fir for 0.01%, poplar for 0.18%, aspen for 0.05%, elm for 0.01%, willow for 0.28%, and saxaul for 0.14%, respectively [1], [3]. The consistency of these quantitative results with data derived from the Multi-Purpose National Forest Inventory conducted between 2014 and 2017 and the Mongolia 2020 State of the Environment Report highlights a clear need to develop a system dynamics model to monitor annual changes in Mongolia's forest resources. Although numerous studies have assessed the status of forest resources, most management decisions continue to rely on static or short-term evaluations. Such approaches don't fully capture long-term interactions among forest regeneration, ecosystem responses, harvesting intensity, and policy interventions, potentially underestimating future risks and opportunities. System dynamic models allow for a comprehensive assessment of the impact of long-term management and policy options, while their use is still limited [21], [22], [23]. The goal of our research is to develop a system dynamic model to predict the future state of Mongolia's forest resources and forest fund areas, and to identify what risks and benefits are likely to arise and when for Mongolia's current forest future. To achieve the objectives of this study, the following goals were established:

- To develop a system dynamics model for projecting future trends in forest area in Mongolia, taking into account changes in environmental conditions, climate, and forest utilization intensity.
- To construct a system dynamics model to forecast the future dynamics of the primary forest resources, focusing on the main tree species composing Mongolia's forest stock.
- By accomplishing these two objectives, the study aims to anticipate the timing and magnitude of potential critical and high-risk conditions in Mongolia's forest resources, thereby informing long-term management and policy decisions.

To achieve the above goals and objectives, this research paper presents the results of the system dynamic model for determining the biomass of the growing larch, cedar, and pine trees, which occupy the highest percentage of Mongolia's forest resources, and the results of the forest fund area dynamic model. These trees account for 94.15% of Mongolia's forest resources, indicating that it is fully possible to determine the future state of Mongolia's forest resources from the state of these trees.

2 Theoretical review study

Forest ecosystems play a vital role in mitigating global climate change by absorbing atmospheric carbon dioxide and storing carbon in biomass and soil pools [4], [5]. While numerous studies have been conducted to assess forest resource conditions, the majority continue to rely on static or short-term evaluation approaches. Statistical analyses and short-term remote sensing methods are effective for estimating forest stock and harvesting levels at specific time points. However, they are inherently limited in capturing long-term interactions among forest regeneration processes, ecosystem responses, harvesting intensity, and policy interventions.

Moreover, studies that integrate economic and ecological impacts within a unified long-term simulation framework remain relatively scarce. This limitation constrains the ability of existing assessment approaches to adequately support participatory and evidence-based forest management decision-making. In particular, comparative evaluations of long-term risks and opportunities based on realistic, case-based management scenarios are insufficiently represented in the current literature.

Consequently, comprehensive studies employing system dynamics modeling to examine the long-term interactions among forest resource dynamics, utilization patterns, regeneration processes, and policy interventions remain limited. Addressing these gaps, the present study adopts a system dynamics approach to evaluate the long-term impacts of alternative forest management, utilization, and regeneration scenarios, thereby providing a decision-support framework for sustainable forest policy and management.

2.1 Forest Fund Area Assessment

The report "Mongolia, Multi-purpose National Forest Inventory 2014–2017" states that "according to the NFO data, the average number of trees with a diameter of 6–15 cm was almost twice as high as the average number of trees with a diameter of 15–30 cm, or 339 stems/ha and 168 stems/ha, respectively. However, the average number of trees with a diameter of 30 cm was 52 stems/ha, which is one-third of the average number of trees with a diameter of 15–30 cm [3]. Preliminary assessment of factors driving forest change in Mongolia: A discussion paper to support the development of Mongolia's National REDD+ Strategy states that "over the past 10 years, an average of 139,000 ha of forest area has been affected by fire, and 34,000 ha have been subject to uncontrolled logging and continued degradation [14].

Table 1. Proportion of Forest Areas Experiencing Degradation and Depletion

Disturbance type	Forest loss (%)	Forest degradation (%)	Non-forest (%)
Fire-affected forest area[1]	2	98	0
Timber-harvested area[1]	10	90	0
Insect-affected forest area[2]	0	100	0
Wind- and snow-damaged forest area[2]	0	100	0
Forest area converted to mining[3]	11.7	0	83.3

Source:

[1] Expert-based estimation considering soil erosion, logging, and grazing impacts
[2] Expert-based estimation
[3] National average forest cover

2.2 Natural Forest Growth, Biomass, and Volume

Wood biomass is essential for estimating forest carbon stocks [6]. The wood biomass equation can be applied to estimate forest biomass and stocks, as well as to assess forest biological productivity and carbon sequestration [7]. Estimating wood biomass provides multiple advantages, including evaluating the broader impacts of the forest sector, predicting future trends, and analyzing the benefits and cost-effectiveness of specific interventions.

The following three allometric equations, which are widely used in tree biomass studies, are used to develop above-ground biomass models of trees [8]. The general form of the allometric relationship can be expressed as:

$$y = a \cdot D^b \tag{1}$$

$$y = a \cdot \left(D^2 H\right)^b \tag{2}$$

$$y = a \cdot D^b H^c \tag{3}$$

Where: y — measured tree volume (m^3), aboveground biomass (kg), D — diameter at breast height (1.3 m above ground)-(cm), H — tree height (m), a, b, c — coefficients of the allometric equation.

The results of the following study also indicated which of the tree biomass equations, Eq. (1)–Eq. (3), best represents the biomass of each forest tree species in Mongolia. A.

Batbaatar et al. (2019) evaluated the fit of allometric equations for five tree species — Siberian cedar, smooth-leaved birch, fragrant poplar, fir, and Siberian larch—and derived the corresponding allometric coefficients. They concluded that the developed equations "provided the best fit for predicting the biomass of wood components and the total aboveground biomass (AGB). The coefficient of determination (R^2) for leaf and branch biomass was 0.83 and 0.93, respectively, and for stem and total AGB it was 0.99 and 0.98, respectively. With the exception of leaf biomass of smooth-leaved birch (74.7%), the equations were able to predict the biomass of most components using the variables D and H with an accuracy exceeding 80.0% [9]."

Also B.Altanzagas et al. 2022 and Ch.Dorjsuren et al. In 2021, the stem biomass of newly planted trees in the Ereeni Ridge, Daguur, was measured as follows: 149.9 ± 40.86 kg for Siberian larch, with the stem accounting for 76.1%, branches 15.3%, and leaves/needles 8.6%; 88.83 ± 35.89 kg for Chekanovsky larch, with the stem accounting for 61.6%, branches 30.6%, and leaves/needles 7.8%; and 216.8 ± 70.69 kg for Forest pine, with the stem accounting for 75.5%, branch biomass 16.8%, and needle biomass 7.6%. Allometric equation models were developed to estimate stem volume and above--ground biomass of Ereeni Ridge Forest Pine, Daguur, and Chekanovsky Siberian larch based on tree diameter at breast height (D) and tree height (H). Two methods were used to model the working position of the tree and aboveground biomass The logarithmic equation with the variable $\ln y = \ln a + b \cdot \ln D + c \cdot \ln H$, and the logarithmic equation with the combined one-dimensional model $\ln y = \ln a + b \cdot \ln(D^2 \cdot H)$ are more effective. These models can be applied to estimate stem volume and aboveground biomass of Ereeni Ridge Forest Pine, Daguur, and Chekanovsky Siberian larch, to establish baseline levels of forest greenhouse gas emissions, and to evaluate measures aimed at reducing emissions resulting from forest depletion and degradation [10], [11].

In this study, previously developed allometric equations and coefficients were applied to estimate the above-ground biomass of three major tree species in Mongolian forests, namely cedar, Siberian larch, and Scots pine. These equations were derived in [8]- [11] studies and are presented below.

1. Cedar

$$\text{Stem biomass: } \ln y = -3.128 + 0.889 \cdot \ln(D^2 H) \tag{4}$$

$$\text{Branch biomass: } \ln y = -4.939 + 0.98 \cdot \ln(D^2 H) \tag{5}$$

$$\text{Needle biomass: } \ln y = -4.395 + 0.748 \cdot \ln(D^2 H) \tag{6}$$

$$\text{Total AGB: } \ln y = -2.736 + 0.889 \cdot \ln(D^2 H) \tag{7}$$

2. Siberian Larch

$$\text{Stem biomass: } \ln y = -3.818 + 1.849 \cdot \ln D + 1.053 \cdot \ln H \tag{8}$$

$$\text{Branch biomass: } \ln y = -3.060 + 3.263 \cdot \ln D - 1.474 \cdot \ln H \tag{9}$$

$$\text{Needle biomass: } \ln y = -3.701 + 2.736 \cdot \ln D - 1.315 \cdot \ln H \tag{10}$$

$$\text{Total AGB: } \ln y = -3.048 + 2.111 \cdot \ln D + 0.552 \cdot \ln H \tag{11}$$

3. Forest pine

$$\text{Stem volume: } \ln y = -12.864 + 1.183 \cdot \ln D + 2.865 \cdot \ln H \tag{12}$$

$$\text{Stem biomass: } \ln y = -4.306 + 1.655 \cdot \ln D + 1.496 \cdot \ln H \quad (13)$$

$$\text{Branch biomass: } \ln y = -4.705 + 2.388 \cdot \ln(D^2 H) \quad (14)$$

$$\text{Needle biomass: } \ln y = -4.03 + 2.003 \cdot \ln(D^2 H) \quad (15)$$

$$\text{Total AGB: } \ln y = -3.612 + 1.941 \cdot \ln D + 1.006 \cdot \ln H \quad (16)$$

Also, in the "Mongolian Multi-Purpose National Forest Inventory" 2014-2017 report, the tree height formula is defined as follows, depending on the diameter at breast height (DBH) of the tree [3].

$$H = a \cdot D^b \quad (17)$$

where: H – tree height (m), D – diameter at breast height (cm, measured at 1.3 m above ground), a, b – allometric coefficients.

The report also determined the coefficients a and b of Eq. (17) for each of the 19 tree species registered in the Mongolian Forest Reserve. For larch, Eq. (17) is determined as $a = 2.0273, b = 0.6215$, and the coefficient of determination $R^2 = 0.66355$, while for pine, equation Eq. (17) is determined as $a = 2.1209, b = 0.6157$, and the coefficient of determination $R^2 = 0.67346$. For cedar, Eq. (17) is determined as $a = 1.7843, b = 0.6328$, and the coefficient of determination $R^2 = 0.66401$ [3]. This means that the coefficients a, b of equation Eq. (17) can be more than 63 percent accurate.

In our model calculations, we directly used equations Eq. (4)-Eq. (16), which are the best-fitting equations calculated by industry scientists for each Mongolian forest tree species, to determine the biomass of each tree species. Furthermore, the biomass equations for each tree species were reformulated as functions of a single independent variable, namely the diameter at breast height D, by substituting the height–diameter $H(D)$ relationship Eq. (17), derived from the 2014–2017 "Mongolian Multipurpose National Forest Inventory" report, into Equations Eq. (4)-Eq. (16).

Therefore, for each tree species, it is possible to determine the total biomass of the tree species by determining the age-dependent D for that tree. This allows us to use the average age of each forest tree species in Mongolia to calculate how forest resources will change using a system dynamics model.

2.3 Age Structure of Mongolian Forest Trees

Trees should be divided into specific age groups according to their age. If we consider the current broadleaf and coniferous forest resources of Mongolia according to technical criteria and classify them by age group, 0.57 percent of the total resources are young forests, 11.49 percent are middle-aged forests, 14.1 percent are maturing forests, and 73.8 percent are mature and old forests (Table 2). In other words, while 87.1 percent of Mongolia's forest area is made up of 50-200-year-old forests, only 5.1 percent are under 50-year-old forests Fig. 1 [3]. This creates a need for sustainable forest management in the long term. Also, the average age of larch forests, which make up 79.28% of the forest resources, is 138.6 years as of 2020, cedar forests, which make up 8.91%, are 146.9 years, and pine forests, which make up 4.95%, are 116.3 years, according to the "Mongolian Forest Fund" report issued by the Forest Research and Development Center [1].

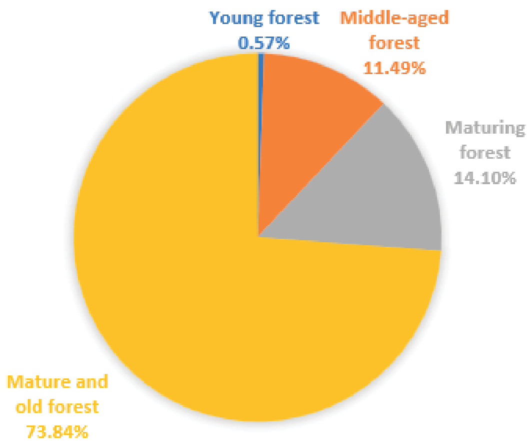


Figure 1 Proportion of Forest resources by Age Class

Table 2. Classification of tree ages in Mongolian forests

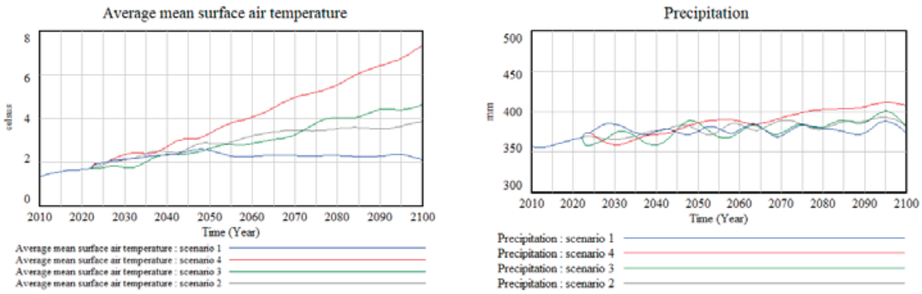
Age class	Age (years)	Forest growth stage
I	≤ 20	Planted and naturally regenerated young trees
II	20–50	Young forest
III	50–100	Middle-aged forest
IV	100–200	Maturing forest [1]
V	200–300	Mature and old forest[1]
VI	≥ 300	Old forest

[1] Depending on species characteristics.

2.4 Climate Change and Its Impact on Soil Moisture

Mongolia is one of the most vulnerable countries to climate change, with an average temperature increase of 2.1°C over the past 70 years. We used the results of our dynamic model to calculate the future trends of precipitation Fig.2b, average temperature Fig.2a, and drought index for Mongolia from the World Bank Climate Change Knowledge Portal Fig.2. Based on this information, we used past and future values of precipitation and average temperature to determine the moisture content Fig.3a and moisture ratio Fig.3b of forest soil [12], [13]. This is one of the main factors influencing the estimation of future growth of forest resources.

In constructing a dynamic soil moisture system model (Richard G Dudley, 2011) [15], the basic idea of a dynamic soil moisture system model based on precipitation was used, and the effect of temperature was added to it.



(a) Temperature trend (b) Precipitation trend

Figure 2 Climate Change in Mongolia

(a) Soil moisture content (b) Soil moisture ratio

Figure 3 Soil Moisture Content and Soil Moisture Ratio in Mongolia

3 Results and Discussion

Drawing on the findings, statistical analyses, and reported data from the studies examined in the previous sections, we developed a system dynamics model to represent the forest fund area and natural forest resources of Mongolia.

3.1 System dynamic model of Mongolian forest fund area

A dynamic model of the forest area was developed based on the forest area schematic and the future trends in forest fund area change were determined Fig. 4. In the dynamic model of the system shown in Fig. 4, the future trend of each area belonging to the forest fund scheme is determined by continuously changing the average of the general distribution of the past and the results of studies conducted by other scientists. For example, when determining the future trend of the area affected by fire, the distribution of the area affected by fire in the future is determined by the statistical average of the area affected by fire from 2010 to 2024. In addition, the changes in the areas affected by forest loss and degradation, depending by Fire-affected forest area, Timber-harvested area, Insect-affected forest area, Wind- and snow-damaged forest area, and Forest area converted to mining, were reflected in the model using the research results shown in Table 2, so that the future trends of the area will change. The results of the dynamic model presented in Fig. 4 are comprehensively illustrated in Fig. 5.

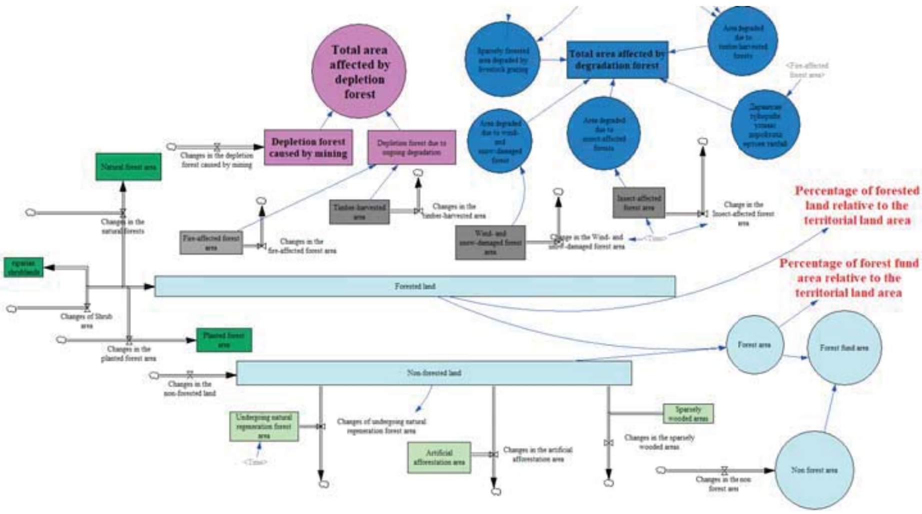
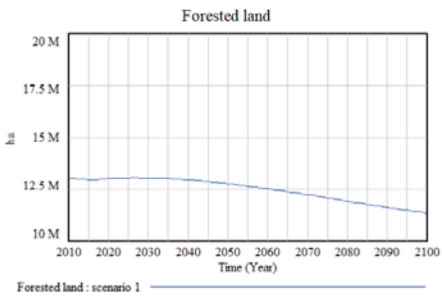


Figure 4 System dynamic model of Mongolian forest fund area*

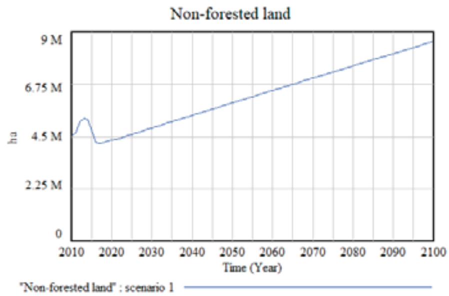
* In the system dynamic model of Mongolian forest fund area shown in Fig. 4, some variables are hidden from view.

According to our system dynamics model, the share of forest land in Mongolia's total area will remain relatively stable (Fig. 5e), but the share of forested land in total area is expected to decline from 8.07% in 2020 to 7.6% by 2080 (Fig. 5a and Fig. 5f). The share of degraded and depleted forest land is also expected to increase to 2–3 times the current level(Fig. 5c and Fig. 5d). Our results are consistent with the results of [25] and confirm that the results of this model are consistent with the predictions of previous researchers. This research work concludes that "Mongolian forest area is generally relatively stable, but spatially some areas have decreased and some have recovered. This indicates that Mongolia's forest area is stable but not significantly increasing."

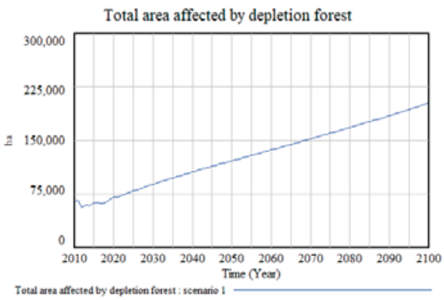
The study indicates an increase in forest depletion and degradation, accompanied by a noticeable trend of land conversion from forest to non-forest areas, which consequently leads to the expansion of non-forest lands. Also, the increase in the area degraded and depleted forest land is another reason for the decrease in the number of living trees per hectare of forest area and the increase in the area with dead, damaged, dried, and decayed trees. These changes are likely to result in multiple negative consequences, including increased greenhouse gas emissions from the forest sector and a reduction in the ecological and economic value of forests. This highlights the critical need for the timely implementation of effective forest management, encompassing protection, utilization, and maintenance measures.



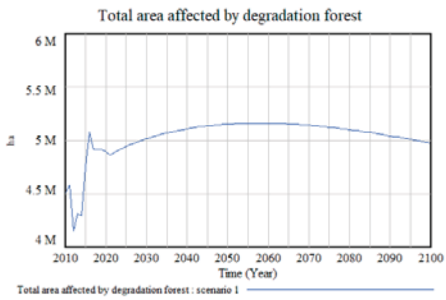
(a) Forested land trend



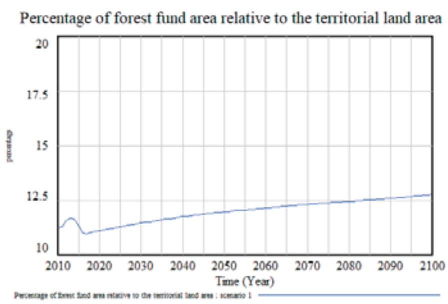
(b) Non-forested land trend



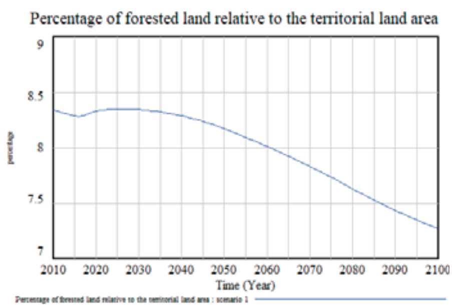
(c) Depletion forest land trend



(d) Degradation forest land trend



(e) Share of forest fund area relative to total land area (%)



(f) Forested land as a percentage of total land area (%)

Figure 5 System Dynamics Model Results for Forest Fund Area Status in Mongolia

3.2 System dynamic model of Mongolian forest resources

A system dynamic model of the growth of natural forest resources per 1 ha of area was developed to show how Mongolia's natural forest resources will change in the future for three tree species: larch, cedar, and pine Fig. 6.

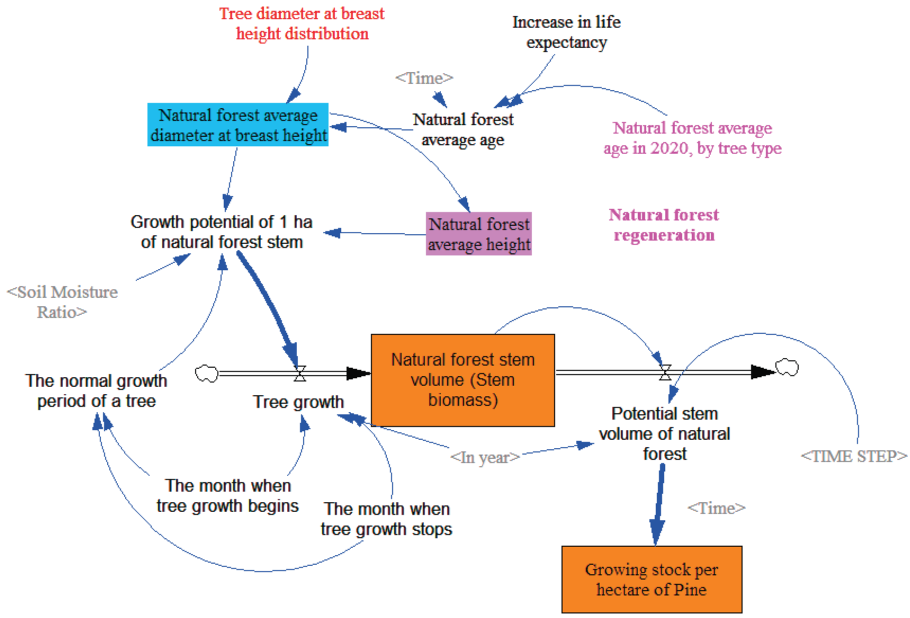


Figure 6 System dynamic model of Natural forest shock (Stem biomass)

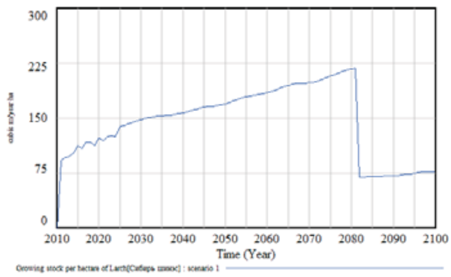
The changes in tree diameter at breast height were distributed according to a normal distribution depending on tree age [16], [17], [19]. Based on the mean age of each tree species [1], the number of trees per hectare was allocated accordingly [3], [18]. The growth dynamics of each species were then modeled using the selected growth equations (Equations (4)–(16)), which were incorporated into the simulation framework.

In addition, the soil moisture ratio was explicitly included in the model, allowing the biomass growth of forest trees to vary proportionally in response to changes in moisture conditions. This modeling approach was conceptually supported by the findings reported in [27], where the relative yield of wheat was shown to depend on variations in air temperature and moisture availability. By analogy, the present study assumes that forest biomass growth exhibits a similar sensitivity to environmental factors, particularly soil moisture, thereby enhancing the ecological realism of the model.

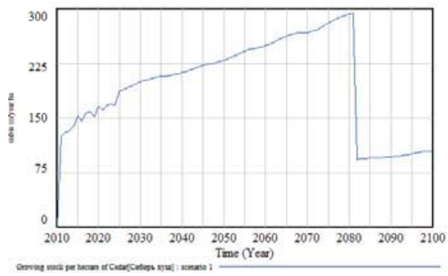
In this study, we adopted concepts based on expert definitions in the field. There is: Forest (living) stock was defined as the total volume (biomass) of all trees with a diameter at breast height greater than 6 cm [20]. To estimate forest stock, we calculated the biomass of tree stems using the model presented in Fig. 6. Given that natural forests do not receive regular maintenance or irrigation, variations in precipitation, temperature, and drought conditions were incorporated. Accordingly, soil moisture was included in the model as a key factor influencing forest stock growth, with its dynamics linked to changes in precipitation, temperature, and the drought index. The results obtained from the system dynamics model are presented in Fig. 7.

According to our model, the reserve per hectare of pine forest registered in the Mongolian Forest Fund is projected to increase steadily until 2041 (Fig. 7c), while the reserve per hectare of larch (Fig. 7a) and cedar (Fig. 7b) forests is expected to increase steadily until 2081. However, the living stock of pine forests is projected to decline by 2–3 times from 2042 (Fig. 7c), and that of larch and cedar forests from 2082 (Fig. 7a and Fig. 7b). These trends indicate that these forests will reach maturity, cease significant growth, experience drying, and begin to deteriorate. The model also suggests a risk of decreasing natural forest area accompanied by an increase in areas affected by depletion. The study used the most appropriate equations calculated by scientists in the field for each Mongolian forest tree species to determine the biomass of the three tree species. The results of the study highlighted that these equations can represent more than 80% of the stem, branch, trunk, and aboveground biomass of each of the three tree species, so we used these equations directly in our model. We also added climate effects to our model. [26]. Therefore, the research team believes that our model was able to accurately represent the biomass of the three tree species by more than 80%, and our research results and predictions confirm the predictions made by experts in the field [24].

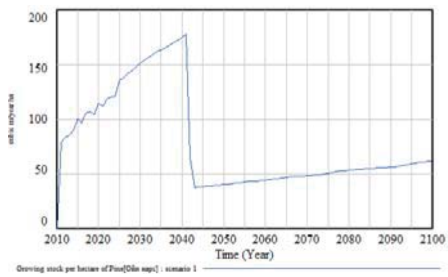
Based on these findings, we conclude that clearing degraded areas within existing natural forests and replanting in the same locations can help reduce the average age of forests and mitigate potential future shortages of forest resources.



(a) Forest stock per hectare for Larch



(b) Forest stock per hectare for Cedar



(c) Forest stock per hectare for Pine

Figure 7 Forest stock per 1 ha of forest area, by tree type

4 Conclusion

Forest ecosystems play a critical role in maintaining ecological stability, supporting livelihoods, sequestering carbon, conserving biodiversity, and regulating hydrological regimes. However, their structure and functioning are increasingly being altered by anthropogenic activities and climate change. Consequently, the sustainable management of forest resources in ecologically and economically sensitive regions presents a major challenge for policymakers and resource managers. The results of our system dynamic model of the Mongolian forest fund indicate that the share of forest fund area in the total area will be relatively stable, but the share of forested area in the total area is expected to decrease from 8.07% in 2020 to 7.6% by 2080. It is also expected that the rate of forest degradation and depletion in forest areas will increase, and the area converted to depletion forest will be 2–3 times higher than the current level. Our results are consistent with the results of [25] and confirm that the results of this model are consistent with the predictions of previous researchers. The increase in forest depletion and degradation has led to a transition of land from forested to non-forested areas, resulting in an observable expansion of non-forest land. This trend is primarily driven by multiple factors, including unsustainable exploitation of natural forests, the impacts of climate change on natural processes, and the lack of coordination in forest sector management policies. Furthermore, the expansion of degraded and depleted forest areas is compounded by a reduction in per-hectare living biomass, accompanied by an increase in areas containing dead, damaged, dried, or decayed forest stock.

Furthermore, larch, cedar, and pine are the dominant tree species in Mongolian forests, collectively accounting for 94.15% of the total forest resources. A system dynamics growth model was developed for these three species, which constitute the majority of Mongolia's natural forest resources, to project potential future changes in forest resource dynamics. The high average age of the tree species that dominate Mongolia's natural forests is likely to pose multiple future risks, including the depletion of forest resources, adverse impacts on environmental conditions and the growth of plant and animal populations, a reduction in greenhouse gas sequestration capacity, and the disruption of forest ecological balance.

Therefore, this model was developed to anticipate potential risks and to support the implementation of appropriate management measures. The model results indicate that the high average age of larch forests, which account for 79.1% of Mongolia's forest resources, has led to a reduced capacity for natural regeneration. Consequently, the increasing proportion of dead, damaged, dried, and decayed trees is expected to significantly reduce forest (living) resources. By 2082, the forest resources of larch forests are projected to decline by approximately 1.7 times relative to current levels. Similarly, the forest resources of cedar forests, which constitute about 9% of the national forest resources, are expected to decrease by 1.5 times by 2082, while those of pine forests, accounting for 4.95%, are projected to decline by 1.8 times by 2041. Our model results support the hypothesis in [24] that "if current trends in exploitation and degradation continue, forest cover is likely to decline in some regions."

These findings underscore the urgent need for the long-term implementation of effective forest management strategies encompassing protection, sustainable use, and maintenance.

This will lead to many negative consequences, including increased greenhouse gas emissions from the forest sector, a decrease in the ecological and economic value of forests, and other negative consequences. Such a substantial decline in forested area and forest resources indicates a very high risk of reduced greenhouse gas absorption capacity and increased greenhouse gas emissions, which are critical indicators of a favorable living environment for the population. This risk is observed in the following manner from the results of our model calculations.

Mongolia's greenhouse gas absorption is expected to gradually decrease from its current level to 23.8 million tons in 2050 and 18.45 million tons in 2100. However, as Mongolia's GDP continues to grow, greenhouse gas emissions from it are expected to increase to 148.4 million tons in 2050 and 538.2 million tons in 2100. This means that Mongolia's current forest reserves will reduce greenhouse gas emissions by 16% in 2050 and 3% in 2100.

From this, we conclude that Mongolia is a clear indication of the urgent need to increase forest resources and implement measures to reduce greenhouse gas emissions in an efficient and correct manner in order to achieve the requirement that "countries should make optimal use of the global carbon market as specified in Article 6 of the Paris Agreement, the bilateral and multilateral cooperation mechanisms of the three Rio Conventions of the United Nations Framework Convention on Climate Change." The model developed in this research work is also a highly valuable model for predicting what measures can be implemented to ensure sustainable management of the forest sector and what results can be achieved by such measures through experimental simulations and evaluations. The research team emphasizes that this is a model of great research and practical importance to support decision-makers.

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